THE RESISTANCE OF BREAKDOWN IN TRANSFORMER OIL

J. Kúdelčík

Žilinská univerzita v Žiline, Elektrotechnická fakulta – Katedra fyziky
Univerzitná 1, 010 26 Žilina, e-mail:kudelcik@fyzika.uniza.sk

Summary The conditions under which breakdown of composite liquid - solid insulation can be occurred, e.g., in transformer, play an important role in designing of such insulation. The initial state of breakdown development is explained on the basis of bubble theory and formation of a plasma channel between the electrodes. The electrical resistance of plasma channel is calculated using several theories and its changes from a few ohms to a few hundred milliohms due to Joule heating caused by high arc current which flows through the plasma. The dynamics of the arc current depends on the parameters of outer circuit and is represented by RLC circuit.

1. INTRODUCTION

An understanding of the way in which the resistance of the spark channel varies, as a function of time, is important not only for better comprehension of liquid discharges but also in various industrial applications [1] where electric sparks are used. It has been reported in numerous publications, that dielectric breakdown is based on complex interactions of hydrodynamic and electronic phenomena [2, 3, 4]. Unlike gases, there is no single theory that has been unanimously accepted to describe the breakdown in liquids.

The breakdown in liquid dielectrics can be described by two basic theoretical theories: electron and thermal. In electron theory [5], all processes develop in liquid and this is identical with theory of streamers generation in gases. In thermal theory [6], [7], the breakdown develops in existing bubbles (regions with lower density), that were generated by conducting current in liquid and local heating. This mechanism is based on the experimental observations of extremely large currents just before breakdown. These high current pulses are believed to originate from the tips of the microscopic projections on the cathode surface with densities of the order of 1 A/cm^3. These high-density current pulses give rise to localize heating of the oil which may lead to the formation of vapour bubbles. The vapour bubbles are formed when the energy exceeds 10 W/cm^3. When a bubble is formed, breakdown follows either because of its elongation to a critical size, or when it completely bridges the gap between the electrodes. In either case, it will result in the formation of a spark. According to this mechanism, the breakdown strength depends on the pressure and the molecular structure of the liquid.

The combination of these models is bubble model [2, 8], where thermal processes are dominant for time of order μs and small electric field and electron processes are important at shorter times, higher electric field or pulses of shorter duration. All processes during breakdown are also dependent on other mechanisms, which play role on interface of the liquid and surface of electrodes (Lippmannov phenomena, Augerov effect) [9].

The aim of the research reported in this article is to describe the time development of resistance of plasma channel in transformer oil using electrical detection techniques and theoretical works.

2. NUMERICAL THEORIES OF ELECTRICAL BREAKDOWN IN DIELECTRIC LIQUIDS

The principal difference between breakdown in gases and breakdown in liquids is the density of the medium. The higher density of liquids makes them more difficult for breakdown, i.e., it requires a higher electric field. One of similar parameters are radius and resistance of plasma channel. For breakdown in gases there are many models, which calculate arc radius and resistance from characteristics of experiment – development of arc current.

Many works describe, that the temporal variation of the channel arc radius is given by:

$$a(t) \approx k \int_0^t I(\tau)^{2/3} \mathrm{d}\tau , \qquad (1)$$

where $I(\tau)$ is the current in channel arc in Amperes, constant $k = 4.7\,\rho^{-1/6}$ and ρ is density of air.

From works by Engel et al. [10] and Montano et al. [11] it can be seen that Kurshner model [12] provides the best approximation of the temporal variation of the gas arc resistance also for time t > 0.5 μs. In their model resistance of plasma channel is described by formula:

$$R_{pl}(t) = \sqrt{\frac{P_0\, d^2}{2\, c \int_0^\tau I(\tau)^2 \,\mathrm{d}t}} , \qquad (2)$$

where model constant c = 24.7, initial pressure in gas is $P_0 = 1.1\times10^5$ Pa, d is gap distance and $I(\tau)$ is current in the channel.

Based on work by Kijonka [13] it can be calculated resistance of plasma channel in air as ratio of energy breakdown and current in transformer oil. Corresponding values of breakdown energy, can be calculated by integration of measured values of current $I(t)$ and potential difference $\Delta U(t)$. Values of current energy, can be calculated as integral of measured current square, as function of time. This model requires simultaneously measurement of voltage development on the electrodes of system what is not easy and very complicated.

In present time also theoretical models of arc resistance in water [3, 4] are presented. Timoshkin et al. [3] describe the formation and development of a highly conductive plasma channel between electrodes immersed in water. Their present model is the self-consistent calculation of plasma channel time-varying resistance. The processes in plasma channel are calculated using the energy balance equation and the equation describing the current in an under-damped pulse driving circuit. From the analysis of their model, it also results that with development of plasma channel its resistance decreases to minimal value - several hundred mΩ. This value decreases with input energy. The arc generates high-power ultrasound and its properties are described in this model, too.

Gurovich et al. [4] in their model derived the normalization differential equations, which determine the processes of underwater wire initiated discharge. In their equations the energy conservation law for wire material evaporation and the dependence of plasma conductivity on the energy dissipated in the discharge are implied to calculate the time varying arc resistance. The arc resistance R_{pl} is time dependent and its time development can be derived by differential equation of Gurovich:

$$\frac{\mathrm{d}R_{pl}(t)}{\mathrm{d}t} = \frac{R_{pl}(t)^3 C^2}{B}\left(\frac{\mathrm{d}U(t)}{\mathrm{d}t}\right)^2, \tag{3}$$

where C is capacitance of the circuit, $U(t)$ is time development of applied voltage and B is constant.

3. EXPERIMENTAL SETUP AND RESULTS

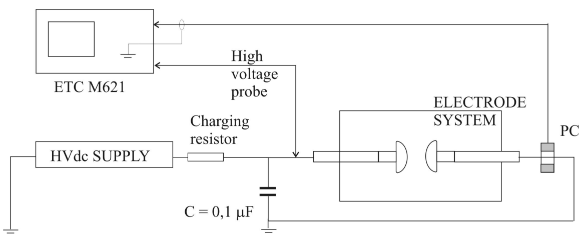

Fig. 1. Experimental setup

Figure 1 shows the schematic diagram of the experimental setup, which includes HVdc power supply TESLA BS 221, electrode system and electric diagnostic. As the electrode system, sphere-to-sphere electrodes with radius 1 cm were used. Electrode distances S were measured with accuracy of 0.01 mm. As a dielectric liquid, new ITO 100 was used. The applied voltage was measured by high voltage probe and the current was measured by means of Pearson coil (110A) with a temporal resolution 20 ns. Development of current and voltage were measured using 150 MHz external oscilloscope ETC M621.

The development of arc current in dependence of applied voltage, capacitance and various electrode distances was measured. In the Fig. 2 the development of arc current I, voltage U on anode and potential difference ΔU across electrode separation can be seen. Arc current is characterized by damped oscillation and its characteristics depended on outer parameters. From this is interesting that potential difference is only several hundred-voltage although breakdown voltage is 3 kV. At the same value of capacitance only amplitude and duration of arc current change with applied voltage. The measurements were also made at various electrode distances (0.1, 0.2 and 0.3 mm) [14] and similar developments of arc currents as were observed in the Fig. 2. Simple measurements in transformer oil were also made by Marton [15], in water by Timoshkin et al. [3] and in air by Wort [16] and Kijonka et al. [13].

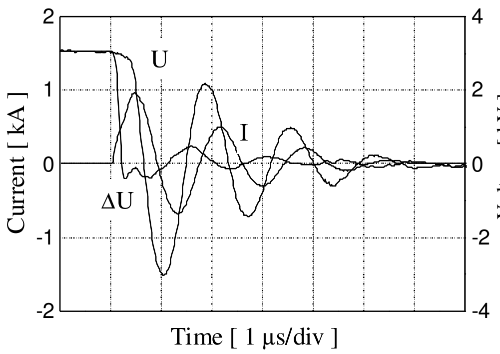

Fig. 2: Development of arc current and voltage across gaps at voltage 3000 V in ITO 100 and gap distance of 0.3 mm.

A series RLC circuit can approximate electric behavior of observed arc current [14]. The development of arc current can be fitted by function Sine Damp:

$$I(t) = I_0 e^{-t/\tau} \sin(\omega t), \tag{4}$$

where parameters I_0, τ, ω are determined by interpolation of measured pulses of arc current. The same conclusion was made in work [3].

From the measured arc current and using the formula (1) time development of arc radius was calculated. The arc radius for different applied voltage is shown in Fig. 3. From figure it can be seen, that arc radius rises with time.

The time varying behavior of resistance of plasma channel calculated by two different theories [12, 4] are shown in Fig. 4. On the base is of measured current (Fig. 3) it was calculated using formula (2) curve I. By solution of differential equation (3) and known development of voltage on anode (Fig. 3) it was calculated curve II. Theoretical equation (3) was numerically evaluated for various measured conditions and then "normalized" with the experimental arc resistance at 0.5 µs (approximate time of maximum arc current) in order for a generalized comparison to be made. From comparison results value of B = 0.18. Note that the constant of proportionality B will only shift the resistance curve up or down and does not change its general shape. Curve I. or II. represent time development of arc resistance for gaseous, water case, respective. From the developments of resistance presented in Fig. 4 it can be seen that are very similar.

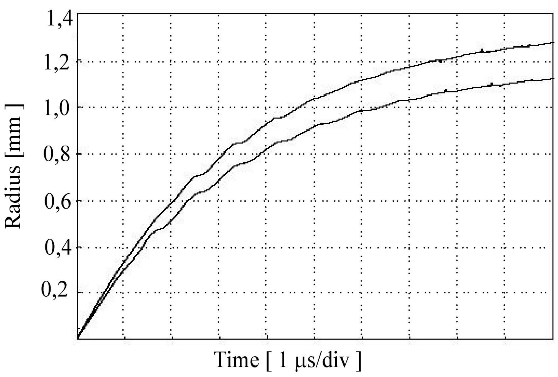

Fig. 3: Time development of arc radius calculated using formula (1) for S = 0.3 mm for applied voltage 3000 V and 3 500 V.

4. DISCUSSION

Based on experimental results and bubble theory, development of breakdown in transformer oil can be divided into three stages: thermal, electronic and RLC circuit. The confirmation of mentioned distribution is supported by experimental results and consistent results from other works [2, 3, 5, 8].

During thermal stage there exist small channels [14] in which transport phenomena take place. At voltage over breakdown voltage, streamer condition is fulfilled and electron avalanches in these small channels can transfer into streamers [2].

In electronic stage one of the streamers bridges the inter-electrode gap and plasma channel is generated with very small conduction and relatively large value of initial resistance $R_{pl}(t=0)$ (see Fig. 4). The creation of plasma channel is very important for the next development of whole breakdown, because it can be simulated from its characteristic values (density, radius and resistance). There are several theories [2 - 5, 8, 10 - 12] that describe dynamic behavior of the plasma channel as its radius and mainly resistance. Development of plasma channel is closely associated with its radius, which increases with time (Fig. 3). Increasing of arc radius with time is caused by energy injected to the breakdown and high pressure inside the plasma channel [3]. Although the arc resistance is a function of channel radius, many models based on this argument give not correctly results [10, 11]. For our type of experiment were only used two models [12, 4], which describe time development of resistance in air and in water. The time varying behavior of arc resistance was obtained by plotted of formula (2) (Fig. 4 – I.) and solution of differential equation (3) (Fig. 4 – II.). Developments of arc resistances presented in Fig. 4 are very similar. So the development of arc resistance in gases has same characteristics as the development of arc resistance in oil. This fact supports the arguments that the breakdown in oil is developed in regions with low density like gaseous channel.

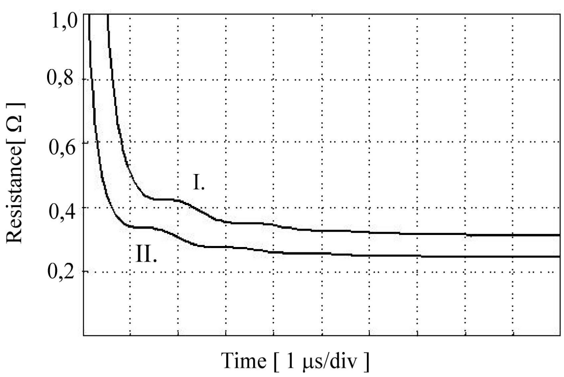

Fig. 4: Time development of resistance of arc channel calculated by Kurshner (2), (I.) and Gurovich (3), (II.) for 3000 V and electrode separation 0.3 mm.

From the previous discussion it can be used knowledge from development of arc resistance in gaseous phase to describe of arc resistance in oil. So as the plasma channel is developing, the current is increasing to the peak value and its resistance is decreasing significantly from a few ohms to a few hundred milliohms (see Fig. 4). This is due to Joule heating caused by high arc current which flows through the plasma channel. The minimum constant value is obtained after 1 µs of breakdown (Fig. 4). Similar characteristics of development of breakdown are presented in other works about breakdown in water [3, 4, 5, 8].

After establishment of breakdown, the development of arc current depends only on parameters of outer circuit and energy stored in capacitor. Now breakdown represents arc resistance as the part of RLC circuit. The minimal value of arc resistance is smaller than resistance of external circuit and therefore it cannot fundamentally influence the development of arc current. During breakdown energy stored in capacitor converts to the system and under dumped oscillation of arc current are observed (Fig. 2, equation (4)). Characteristics of arc current are result of applied voltage and mainly of energy stored in capacitor. Similar development of arc current in water was observed in work by Timoskhin et al. [3] and Wort [16]. In this work [3] also model of RLC circuit was used to describe characteristics of arc current. Breakdown is accompanied with other various processes as acoustical effect, light flash, shock and acoustic waves [14]. After the breakdown quantity of bubbles of various magnitudes were observed.

5. CONCLUSION

The development of breakdown in ITO 100 was described by the bubble theory with three stages. By application of DC voltage to electrodes, the plasma channel between the electrodes was formed. Time development of plasma channel resistance was calculated by two models, which give similar results. Its resistance changes from a few ohms to a few hundred milliohms due to Joule heating caused by arc current which flows through the channel. After establishment of plasma channels, breakdown represents only part of resistance in RLC circuit. The development of arc current is modified by parameter of outer circuit.

Acknowledgement

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